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Model for Path Duration in Vehicular Ad Hoc Networks under Greedy Forwarding Strategy

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Abstract

In this paper, we present an analytical model to find the probability density function (PDF) of link and path duration in vehicular ad hoc networks (VANETs), assuming the distance headway to have lognormal distribution. We then analyze the impact of vehicle mobility and transmission range on the link duration PDF and mean path duration in VANETs. We consider the greedy forwarding strategy to forward message from one hop to the next. Our analytical and simulation results suggest that, the link duration PDF can be approximated as lognormal with appropriate parameterization. We present the Kolmogorov-Smirnov goodness-of-fit test results to justify this claim.

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Keywords: Vehicular Ad Hoc Networks; traffic flow; link life time; reliability

1. Introduction

Vehicular Ad Hoc Networks (VANETs), which allow vehicles equipped with wireless communications devices to form a self-organized network without the requirement of permanent infrastructures, are highly mobile wireless ad hoc networks envisioned to provide support for both safety and non-safety applications by enabling vehicle-to-vehicle (V2V) and vehicle-to infrastructure (V2I) communications [1][2]. The link duration or link life time is the period of time during which two vehicles in the network stay within the transmission range of each other. The link duration has significant influence on the route lifetime, which, in turn, determines the packet delivery ratio and the per connection throughput for a given source-to-destination pair in the network. The lifetime of a multi-hop route is determined by the lifetime of its weakest link, i.e., the link with the lowest life time among all the links constituting the multi-hop route.

The importance of link and path duration on the performance of MANETs has been extensively studied in the literature [3][4][5]. In the case of VANETs, simulation results in [6] confirm that, for both highway and urban environments, both the

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single hop as well as the multi-hop connection life time is an important quality of service (QoS) metric for unicast routing that highly depends on the vehicle density, the channel conditions and the relative speed of vehicles.

Several papers have appeared that deal with the analysis and evaluation of communication link (single hop as well as multi-hop) life time in MANETs [4][7][8][9]. Based on experiments with dynamic source routing, Bai *et al*. [4] propose an approximate PDF for the path duration in MANETs. Pascoe-Chalke *et al*. [7] derive the time duration of an n node path in a MANET. Yueh-Ting Wu *et al*. [8] develop an analytical framework for link duration in multi-hop mobile networks. They show that the link duration for two nodes is determined by the relative speed between the two nodes and the distance during which the link is connected. Wu *et al*. [9] present statistical models to accurately evaluate the distribution of the lifetime of wireless links in a MANET in which nodes move randomly within constrained areas.

In [10], Sun *et al.* propose an analytical model for the probability density function (PDF) of link lifetime under the following assumptions :(i) equally spaced nodes; and (ii) normally distributed vehicle speed. However, their first assumption is not reasonable since, as widely known, inter-vehicle distance is a random variable. Yan *et al.* [11] investigate the probability distribution of the lifetime of individual links in a VANET assuming (i) the PDF of inter-vehicle headway distance to be log-normal, and (ii) the vehicle speed to be deterministic. Empirical studies have shown that, Poisson distribution provides an excellent model for vehicle arrival process and the vehicle speed is a random variable that follows Uniform distribution [12][13]. Liu *et al.* [14] propose expected path duration maximized routing algorithm for cognitive-radio enabled VANETs (CR-VANETs). Barghi *et al.* [15] introduce a new protocol which uses the characteristics of vehicle movements to predict the vehicle behavior and select a route with the longest life time for connecting vehicles to the Internet.

In this paper, we present an analytical model to find the PDF of the link as well as the path duration in one-dimensional VANETs. We assume a position based routing protocol such as greedy perimeter stateless routing (GPSR) [16] that use a greedy strategy for packet forwarding. Position-based routing relies on the knowledge of the geographical position of the nodes to select the best path to forward data to a destination. Thus, when using position-based routing each node must be able to determine its own location and a source node must be aware of the location of the destination node. Under greedy forwarding, the sender forwards the packet to the neighbor that is closer to the destination. The forwarding is continued till the packet reaches the destination. If greedy forwarding fails, GPSR use perimeter forwarding strategy [16]. An analytical model for the link and path duration would be useful for estimation the average link and path duration and for anticipating disruption of the routing path. The model would also be useful towards the design of stable position based routing protocols that maintain reliable routing paths to improve the network performance. Remainder of this paper is organized as follows: The system model, which includes models for the inter vehicle distance and the vehicle mobility, is presented in Section 2. In section 3, we present the analysis of link and path life time under the greedy forwarding approach. The analytical and the simulation results are presented in Section 4. The paper is concluded in Section 5.

2. System Model

In this section, we describe the models for the head way distance and vehicle mobility employed in this paper. Consider the one dimensional VANET formed a single lane highway where all the vehicles move in the same direction. For the analysis of link life time, we assume the probability distribution of the headway distance, to be lognormal [17]. The basis for the lognormal headway model is that a vehicle maintains a safe distance while following its leading vehicle closely at variable speeds. The lognormal headway model has been validated by real traffic measurements [18][19][20][21]. Real world traffic data collected by S. Yin *et al.* [22] shows that the log-normal distribution model is a better choice when fitting headway data when the traffic is in forced flow status. Further, we assume that vehicles on the highway have the same mean velocities, but they are permitted to move with variable instantaneous velocities that are limited to a range of values. This means that each vehicle selects a speed from the range according to a probability distribution. Suppose a vehicle selects a speed independently and uniformly in the range $[v_{min}, v_{max}]$ the PDF of V is given by

$$f_V(v) = \frac{1}{V_{max}-V_{min}} \quad ; \quad v_{min} \le v < v_{max} \tag{1}$$

3. Analysis of Link and Path Life Time

In this section, we present analytical model for the probability distribution of link life time. We assume a fixed transmission range (R meters) and a fixed transmission power for all the vehicles. We do not consider the variability of transmission range arising out of channel randomness or other issues. Consider the one dimensional VANET formed a single lane highway where all the vehicles move in the same direction. As mentioned before, our analysis of link life time is based on a position based routing protocol such as GPSR [16] that use a greedy packet forwarding strategy. An example of greedy forwarding is shown in Fig 1. Here, source vehicle has a packet destined for destination vehicle. Source vehicle's radio range is denoted by the circle about source vehicle. Source vehicle forwards the packet to vehicle B, as the distance between B and destination vehicle is less than that between destination vehicle and any other vehicle within the communication range of source vehicle. This greedy forwarding process repeats, until the packet reaches destination vehicle.

Let X_i be the random variable which represents headway distance. As already discussed above, the most suited headway distance distribution for dense road scenario is lognormal i.e. $X_i \in \log N\ (\mu_i, \sigma_i)$. Let X be the random variable which represents distance between source vehicle and the next hop vehicle. Hence we can write $X = \sum_{i=1}^{m} X_i$, where X_i's are independent log-normal random variables with a common distribution. As illustrated in Fig. 2, X represents the convolution of m independent headway distances [11]. Here the mean and standard deviation of X, i.e., μ and σ can be determined using Fenton-Wilkinson method [23]. Since the inter-vehicle distances are i.i.d. lognormal, by Fenton-Wilkinson approximation, X can be approximated as lognormal i.e. $X \in \log N\ (\mu, \sigma)$. The PDF of X is given by

$$f_X(x) = \frac{1}{x\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}} \tag{2}$$

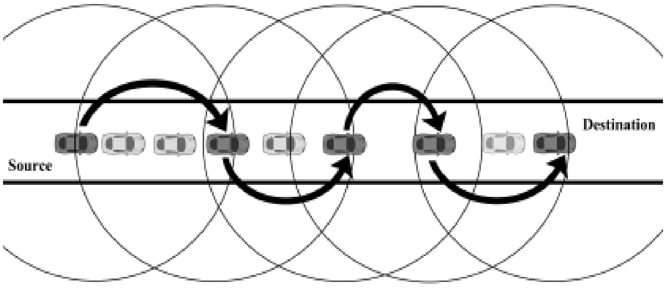

Fig 1: One dimensional VANET and Greedy forwarding Strategy

Consider two vehicles A and B moving in the network, even though they have the same speed statistics, their instantaneous velocities are different. We are interested in the relative movement of one vehicle (A) with respect to the other (B). Let V_A , V_B and V_r respectively be the random variable that represents the velocities of vehicle A, vehicle B and the relative velocity between the given pair of vehicles. Since the relative velocity between the given pair of vehicles $V_r = V_A - V_B$ the dynamic range of V_r is limited to $(-v_m, v_m)$ where $v_m = v_{max} - v_{min}$. Further, the PDF of v_r, $f_V(v_r)$ can be determined by using the principle of random variable transformation and is given by

$$f_{V_r}(v_r) = \begin{cases} \frac{v_{max}-v_{min}+v_r}{(v_{max}-v_{min})^2} & ; \quad -v_m \le v_r \le 0 \\ \frac{v_{max}-v_{min}-v_r}{(v_{max}-v_{min})^2} & ; \quad 0 < v_r \le v_m \end{cases} \tag{3}$$

3.1. Distribution of Link Life Time

Let T be the random variable that represents the time duration for which the communication link between vehicles A and B is active. Now T is computed as follows:

$$T = \frac{X}{V_r} \tag{4}$$

Assuming that X and V_r are independent, the CDF of T, $F_T(t)$ can be obtained as follows:

$$F_T(t) = P(T \le t) = P(X \le V_r t) \tag{5}$$

Using the principle of random variable transformation F_T (t) can be determined as follows:

$$F_T(t) = \begin{cases} F_{T_1}(t) & ; \ t \le \frac{R}{v_m} \\ F_{T_1}(t) - F_{T_2}(t) & ; \ t > \frac{R}{v_m} \end{cases} \tag{6}$$

where $F_{T_1}(t)$ and $F_{T_2}(t)$ are given by

$$F_{T_1}(t) = \frac{1}{2\,{v_m}^2}\Big[{v_m}^2\, erfc\left(\frac{\mu-ln\,(v_m t)}{\sigma}\right) + \frac{e^{\mu+\frac{\sigma^2}{2}}}{t} v_m \left\{1+\mathrm{erf}\Big(\frac{\mu+ln\,(v_m\, t)+\sigma^2}{\sigma}\Big)\right\} - \frac{{v_m}^2}{2}\, erfc\left(\frac{\mu-ln\,(v_m\, t)}{\sqrt{2}\sigma}\right)$$

$$-\frac{1}{2\,t^2} e^{-2(\mu+\sigma^2)} \left\{1+\mathrm{erf}\,\Big(\frac{\mu+2\sigma^2-ln(v_m\, t)}{\sqrt{2}\,\sigma}\Big)\right\}\Big]$$

$$F_{T_2}(t) = \frac{1}{2\,{v_m}^2}\Big[\,erfc\left(\frac{\ln R-\mu}{\sqrt{2}\sigma}\right) v_m \left(v_m - \frac{R}{t}\right) - erfc\left(\frac{\ln R-\mu}{\sqrt{2}\sigma}\right)\left(\frac{{v_m}^2 - (\frac{R}{t})^2}{2}\right) - {v_m}^2\ erfc\left(\frac{\ln\,(v_m\, t\,)-\mu}{\sqrt{2}\sigma}\right)$$

$$-v_m \frac{e^{\mu+\frac{\sigma^2}{2}}}{t}\mathrm{erf}\left(\frac{\mu+ln\,(v_m\, t)+\sigma^2}{\sigma}\right) - \frac{R\, v_m}{t} erfc\left(\frac{\ln R-\mu}{\sqrt{2}\sigma}\right) - v_m \frac{e^{\mu+\frac{\sigma^2}{2}}}{t}\mathrm{erf}\left(\frac{\mu+\ln R)+\sigma^2}{\sigma}\right)$$

$$+\frac{{v_m}^2}{2}\ erfc\ \left(\frac{ln\,(v_m\,t)-\mu}{\sqrt{2}\sigma}\right)-\frac{v_m}{2\,t^2}\ e^{2(\mu+\sigma^2)}\ \mathrm{erf}\left(\frac{\mu+2\sigma^2-ln(v_m\,t)}{\sqrt{2}\ \sigma}\right)-\frac{(R\,v_m)^2}{2t^2}\ erfc\ \left(\frac{\ln R-\mu}{\sqrt{2}\,\sigma}\right)$$

$$+\ e^{2(\mu+\sigma^2)}\ \mathrm{erf}\left(\frac{\mu+2\sigma^2\text{-}\ln R)}{\sqrt{2}\ \sigma}\right)\ ] \tag{7}$$

The average link life time is then computed as follows:

$$E[T]=\int t\ f_T(t)\ dt \tag{8}$$

It may be noted that the average link life time given above does not have a closed form solution; but has to be evaluated by numerical integration.

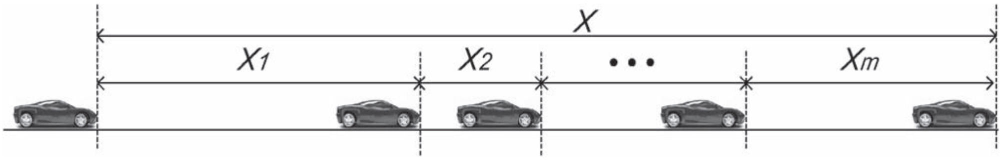

Fig. 2 Distance between source vehicle and the next hop vehicle [11].

3.2. Distribution of Path Life Time

The path duration is one of the key parameters which could be useful to improve the performance and throughput of the network. The probability distribution of path life time can be derived from the distribution of the link duration. Assume that the path from source to destination consists of H number of hops. Let T_i be the life time of link i (i=1, 2, …,H). The path duration can then be expressed as $T_{path}=min(\,T_1,T_2,\ldots,T_H)$. Assuming that T_i's are i.i.d. with PDF $f_T(t)$, the probability density function of T_{path} is determined as follows [24]:

$$f_{T_{path}}(t)=H\ f_T(t){C_T}^{(H-1)} \tag{9}$$

Here $C_T=1-F_T(t)$ is the complementary cdf of T. The average path duration can be estimated as

$$E\left[T_{path}\right]=\int T_{path}f\left(T_{path}\right)\,dT_{path} \tag{10}$$

4. Analytical and Simulation Results

In this section, we present the analytical and the simulation results for the link and path life time and reliability. Both the results are obtained using MATLAB. The analytical results correspond to the mathematical models presented in the previous section. We simulate a highway of length 10 Km where the distance headway is assumed to be lognormal. Further, we assume vehicle speed to be Uniform over (v_{min}, v_{max}).

To find the probability distribution of link and path duration and its average, we take a series of snapshots of the network connectivity graph during the simulations (one snapshot every second). For each snapshot, the connectivity graph can be considered to be static and thus connectivity properties can be analyzed. The link duration is calculated as the interval between the time when the link is created and the time when it breaks. This is done for every link that comes into existence during the simulation. We then plot a histogram of the link duration after sorting the ample values of the link duration. From a large set of measured link duration samples, we use the relative frequency approach to plot its PDF. The average link duration for each link is then determined from the PDF from which the average path duration is calculated. In our simulations we assume that all the vehicles are using same transmit power and have same transmission range.

Fig. 3 shows the analytical and simulation results for the probability density function of link life time for different values of communication range R. The corresponding average path duration is plotted in Fig. 6 for different values of number of hops. Here for a higher communication range R the average path duration is higher. Similarly as the number of hops increases, the path duration decreases. In a multi hop communication scenario when any of the intermediate link breaks the communication path is broken and new path needs to be created. Thus when the number of hops increases, the probability of a breakage in any of the link is higher, which results in the reduction of the average path duration. Fig. 4 shows the analytical and simulation results for the probability density function of link life time for different values of maximum velocity v_{max}. In this case, we keep v_{min}=20Kmph; and R=300m. When the maximum velocity of the vehicles increases, the link duration degrades. This will result in the degradation of the path duration as well. Fig. 7 shows the average path duration for different values of maximum velocity and for different number of hops. The probability distribution of path duration for different values of hop count is depicted in Fig. 5. Here the different parameters selected are v_{max} = 80Kmph, v_{min} = 20Kmph and R=300m.

4.1. Kolmogorov-Smirnov Test

For the communication scenario considered in this paper, we observe that the link duration Probability Density Function (PDF) can be approximated as lognormal given by $f_T(t) = \frac{1}{t\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln(t)-\mu)^2}{2\sigma^2}}$ where $\beta_0 = e^{\mu+\frac{\sigma^2}{2}}$ is the mean link duration. We have performed the Kolmogorov-Smirnov goodness-of-fit test (K-S test) to validate this claim. The test has been carried out as follows: Given $F_1(x)$, the expected hypothesized CDF for the link duration, K-S test compares $F_1(x)$, to $F_2(x)$, the CDF obtained by simulations. The result of K-S test is based on the value of greatest discrepancy between the observed and expected CDF, which is called the D-statistic. The D-statistic is defined as D = max $\|F_1(x) - F_2(x)\|$. We have computed the D statistic values for various settings of maximum vehicle velocity and transmission range. The results are tabulated in Table I. For the best fit CDF curve obtained from the K-S test, we have computed the mean value (β_0) and the results are listed in Table I. Table I also lists the results for the mean link duration (E[T]) obtained from our simulation results. Our K-S test and the corresponding D-statistic results confirm that the link duration PDF can be approximated to be lognormal since the D-statistic values are observed to be quite small (always observed to be less than 0.10).

Table 1. K-S Test Result: D Statistics values

R (meters)	v_{max}(Kmph)	Mean link duration E[T]	D statistics	β_0
100	80	8.35	0.0712	7.98
200	80	8.81	0.0869	8.45
300	80	9.20	0.0860	8.87
500	80	9.93	0.0756	9.61
300	40	10.23	0.0910	9.84
300	60	9.60	0.0723	9.35
300	100	8.54	0.0854	8.29
300	120	8.33	0.0598	8.03

5. Conclusion

In this paper, we have investigated the characteristics of link and path life time in one-dimensional vehicular ad hoc networks (VANETs) formed on single lane highways. Assuming Uniform distributed vehicle speed and lognormal headway distance, analytical expression was derived for the probability density function (PDF) of link life time. We have analyzed the impact of vehicle mobility and transmission range on the average link life time. We then performed the Kolmogorov-Smirnov test to find the best fitting PDF for the link duration. The corresponding D-statistic results showed that the link duration PDF can be approximated to be lognormal. The results of this paper would be useful for the development of reliable routing protocols.

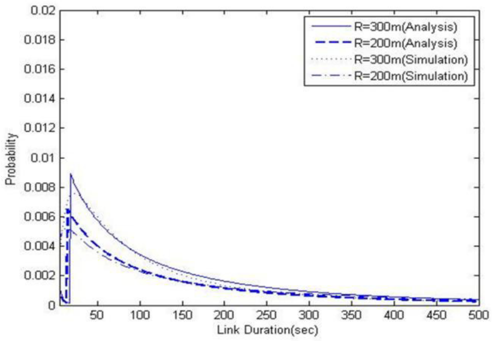

Fig 3. Link duration PDF for different R

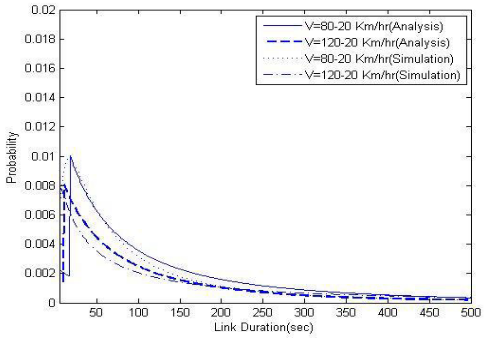

Fig 4. Link duration PDF for different v_{max}

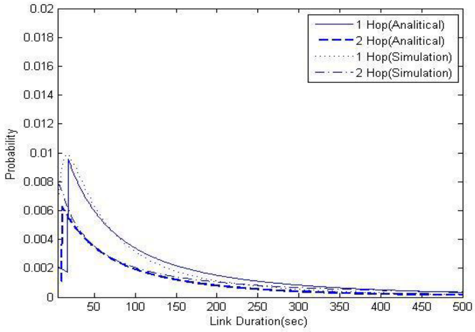

Fig 5 Path duration PDF multi hop connectivity

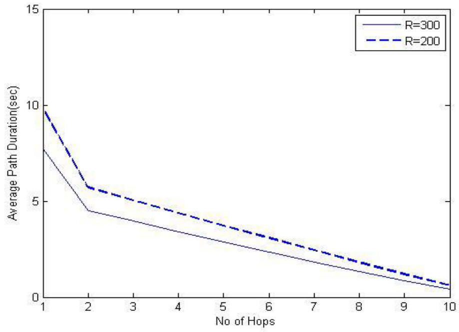

Fig 6: Average path duration versus number of hop

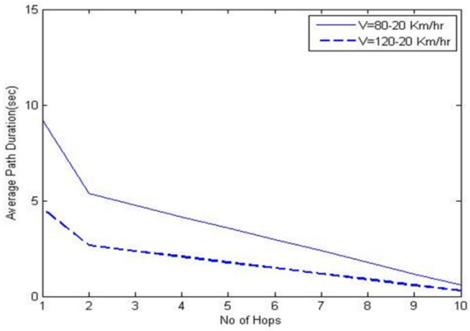

Fig 7: Average path duration vs number of hop

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